Enabling Control in the Minimally Conscious State in a Single Session with a Three Channel BCI

ENABLING CONTROL IN THE MINIMALLY CONSCIOUS STATE IN A SINGLE SESSION WITH A THREE CHANNEL BCI

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Abstract

The study aimed to detect awareness in a single participant, diagnosed minimally conscious for the past 11 years, using an EEG-based brain-computer interface (BCI), and to determine if real-time feedback enhances our ability to detect awareness in a single session. After 90 trials involving motor imagery (MI) with no feedback hand grasp vs. wiggle toes could be classified with ~82% accuracy with only three EEG channels. In the same session we subsequently provided real-time feedback with two games where the participant was instructed to move a ball and a spaceship, respectively, to reach a target by performing the same MI tasks. ~77% ball and 80% spaceship control was achieved. At the outset of the experiment the participant did not seem attentive or interested however after the feedback runs the participant was noticeably more attentive. Family members in attendance at the experiment commented on the noticeable changes in demeanor of the participant who had provided no overt indication of language comprehension or other cognitive function since diagnosis. The results indicate that real-time feedback should be used in the detection of awareness to inform the completely locked-in of the potential of (BCI) technology as a means of communication (i.e., that it is not just another assessment) and motivate engagement.

1. Introduction

Severe brain injury causes a change in consciousness. Consciousness refers to awareness of the self and the environment. The Minimally Conscious State (MCS) is a condition of severely altered consciousness, where there is minimal evidence of any form of awareness. Severely altered consciousness most often occurs as a result of a brain injury. Some injuries are mild and may cause relatively minor changes in consciousness such as brief confusion or disorientation but a condition may arise when someone has gone through a coma into what is known as a vegetative state, where they are "awake" but unaware. Up to 43% of patients diagnosed as vegetative are reclassified as (at the least) minimally conscious after further assessment by clinical experts [1][2] The diagnosis is often given if there are no overt behavioural responses to external stimuli [2]. There is now a lot of evidence suggesting that a subset of patients diagnosed as vegetative actually have some level of awareness. Findings from functional magnetic resonance [1][3] as well as electroencephalography (EEG) studies [2] raise doubts about several of the core principles that underpin diagnosis of the vegetative state and the extent to which clinicians can confirm that a patient is unaware of themselves and their environment. It is therefore critical that new methods are developed and tested to detect awareness in this clinical population and enable those who are aware and capable to provide responses to questions or even communicate desires/feelings.

This study aimed to assess awareness in a person who has been diagnosed MCS for over 11 years using EEG and to determine if it is possible that response and/or control can be achieved using an EEG-based brain-computer interface (BCI). BCI is a relatively new assistive technology which enables users to interact with computers and their environment using their EEG [4]. BCIs utilize a number of self-directed neurophysiological processes such as the activation of sensorimotor cortex during motor imagery (MI) or attempted motor execution. The μ (8-12Hz) and β (13-30Hz) bands are altered during sensorimotor processing [5][6][7]. Attenuation of the spectral power in these bands indicates an event related desynchronization (ERD) whilst an increase in power indicates event-related synchronization (ERS). ERD of the mu band and ERS of the beta band are associated with activated sensorimotor areas and ERS in the mu band is associated with idle or resting sensorimotor areas. ERD/ERS has been studied widely for many cognitive studies and provides very distinctive lateralized EEG pattern differences which form the basis of left vs right hand or foot MI-based BCIs [4]-[9].

Determining if someone in the minimally conscious state can comprehend and follow instructions to perform one of two motor imageries can be achieved by assessing the ERDS patterns or the accuracy in distinguishing one motor imagery from another using only the EEG patterns. This approach was taken by Cruse et al [2] to detect awareness in a cohort of 16 participants who were minimally conscious or vegetative. In one session with no feedback in a right hand vs wiggle toes MI task and up to 200 repetitions (trials), 3 of the 16 participants were shown to be able to follow commands and perform the MI task thus demonstrating that at least a subset were capable of sustained attention, response selection, working memory and language comprehension [2]. The study did not involve real-time feedback during the MI task. There is significant evidence that feedback during motor imagery BCI can enhance class separability and is a requirement to improve sensorimotor learning for controlling a BCI. In the context of this study, gaining or maintaining the attention of someone who is minimally conscious, (or at least overtly so) and who may be in that state for some time and has, perhaps, given up hope, having been subjected to so many assessments and interventions with no successful outcome, real-time feedback is important. Many MC frequently slip in and out of what appears to be a sleep state. Real-time feedback is therefore suggested to ensure the participant experiences the potential for BCI.

This study aimed to follow a similar protocol to that of [2] for detection of awareness, using the same motor imagery tasks and instructions but using less EEG electrodes. The study also aimed to determine if feedback could enhance the detection of awareness or if there were any noticeable differences in the participant's attentiveness as a result of the feedback, and to encourage, motivate and inform the user of the technologies potential should they be aware and capable of undertaking the tasks. The study ultimately aimed to assess if BCI could provide a communication channel for the participant who has not communicated with his family in 11 years.

2. Methods

Participant

One male participant (aged 27) took part in this study. He contracted juvenile posterior Fossa Astrocytoma, diagnosed November 2001, and underwent a partial resection with post-operative cerebral oedema and hydrocephalus requiring insertion of a ventriculoperitoneal shunt. Further extensive posterior fossa surgery was conducted and a follow up scan showed a frontal infarction. The participant was diagnosed with disorder of consciousness thereafter requiring full care for all activities of daily living.

After initial SMART assessment in [10] 2001 the participant met the criteria for minimally conscious state (MCS). The SMART assessment was repeated in 2004 and 2011 and the participant met the criteria for MCS. Table 1 shows the Comma Recovery Scale – Revised (CRS-R) [11] scores (CSR-R total score 4/23). The CRS-R was specifically developed to differentiate vegetative (VS) from minimally conscious states (MCS) and to identify patients that have emerged from MCS. It explicitly incorporates the current diagnostic criteria for VS and MCS into its administration and scoring scheme, and is unique in allowing derivation of a diagnosis directly from the examination findings. Serial Wessex Head Injury Matrix (WHIM) [12] measurements produced a mean score of 8 (range 5-12). All scores, SMART, CSR-R, and WHIM, consistently show the participant was at best minimally conscious. Informed assent was acquired from the participant's family and

Scale	Score
Auditory Function Scale	**1**
Visual function Scale	**0**
Motor Function scale	**1**
Oromotor/verbal function scale	**1**
Communication scale	**0**
Arousal scale	**1**
Total	**4**

Table 1 : CSR-R scores for participant

medical teams and ethical approval was provided by the National Rehabilitation Hospital and University of Ulster's Research Ethics Committees.

Data acquisition procedures

The study was conducted in one day in a session lasting approximately 2 hours at the National Rehabilitation Hospital, Dun Laoghaire, Ireland. The environment was a small room just off a busy corridor in a rehabilitation unit and a number of the medical team was present along with both the participant's parents. Three bipolar EEG channels over the sensorimotor cortex (around positions CP3-FC3, CPz-FCz and CP4-FC4) were recorded with a reference electrode placed at FPz. A four channel g.MOBIlab mobile EEG amplifier and g.GAMMAsys active electrode system (both from Guger Technologies, Austria, www.gtec.at) were used to acquire the EEG at a sample rate of 256Hz. The signals were band passed filtered between 1-30Hz. The participant sat in front of laptop computer in a motorized wheelchair with head held upright with a head strap.

Detection of Awareness

The first run in the session followed a similar protocol to that used in [2]. Squeeze right-hand and wiggle toes MI were performed in 6 blocks of 15 trials. 3 block of each type of motor imagery were performed and no two consecutive blocks involved the same MI. Each block began with the visual and auditory presentation of the task instructions for that block. The instructions were: "Every time you hear a beep and/or see an arrow on the screen, try to imagine that you are squeezing your right-hand into a fist and then relaxing it/wiggling your toes. Concentrate on the way your muscles would feel if you were really performing this movement. Try to do this as soon as you hear each beep or see the arrow". After 5s, the instructions were followed by the binaural presentation of 15 tones (600 Hz for 60 ms) synchronized with a cue arrow appearing on the screen according to the timing presented in Figure 1(a). The inter trial interval was between 1 and 2s chosen randomly. Each block concluded with an instruction to relax. There was short break of 1–2 min before the start of the next block.

The protocol differed from [2] in that the instructions and cues were presented both aurally and visually. Also, after the first block, it was noticed that the participant had closed his eyes and may have fallen asleep. For the remaining blocks one of the medical team sat viewing the participant and provided verbal instruction for some trials (imagine wiggle toes or squeeze right hand) if the participant appeared to be disengaging/falling asleep, to ensure engagement in the task as much as possible.

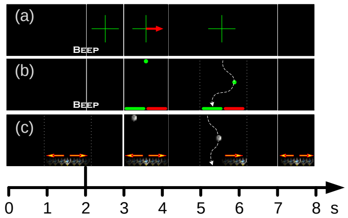

Figure 1. (a) basic training no feedback (b) ball feedback (c) spaceship game paradigm (without background graphics)

Analysis and the BCI

Subject-specific frequency bands were selected automatically in the range 1-30Hz and neural time-series prediction pre-processing (NTSPP) [8][9] was employed using neural networks in conjunction with common spatial patterns (CSPs) with linear discriminant analysis (LDA). Further information on the BCI translation algorithms are presented here [8][13]. Features are derived from the log-variance of preprocessed/surrogate signals within a 2 second sliding window. A 20-fold inner-outer cross-validation (CV) was performed to find the optimal parameters. A feature set was extracted and classifier trained at every time point across the trials and tested for that point on the outer test folds. The average across the 20-folds was used to identify the optimal number of CSPs and the final time point of peak mean classification accuracy (mCA) was used to setup the classifier used for real-time feedback.

Real-time feedback

After the BCI was setup on the run 1 (90 trials) the participant took part in feedback experiments using the standard ball-basket paradigm shown in Figure 1(b). The run consisted of 61 trials where the participant had to direct the ball into one of two baskets positioned on the left or right at the bottom of the screen in each trial. The target basket was green. The ball fell continuously for 3s and could be directed to the left and right using wiggle toes and squeeze right hand MI, respectively.

Following a short break after run 2 a second feedback paradigm was introduced which involved moving an onscreen spaceship left and right using either MI to dodge asteroids which fell from the top to the bottom of the screen as shown in Figure 1(c) [13]. (video available here [14]). For both feedback paradigms the participant was given verbal instruction on how to control the feedback and for the initial 4 trials and periodically during each of the runs the participant was verbally prompted with the correct MI to perform to motivate/encourage attentiveness.

Classification and statistical analysis

Mean classification accuracies (mCA) from 20-fold cross validations on each of the 3 runs are reported. mCA is calculated at the rate of the sample interval (for every time point) using a 2s sliding window. Only baseline mCA (500 ms before cue onset) and peak mCA (in the event related period) are compared to determine that there was a statistically significant difference between baseline performance and MI. Both a parametric *t*-test

Run	**Trials Toes/ Hand**	**C* [%]**	**mCA 500ms⁺ [%]**	**Peak mCA**	**t-test *p***	**Wilc. *P***
NoFB	45/45	59	56.25	82.50	0.001	0.002
Ball	26/35	64	50	77.50	0.007	0.016
Game	25/17	65	53.33	80	0.057	0.094

*Appox. upper confidence limits of a chance result for number of trials (alpha 0.01) (see [15]). ⁺Before cue

Table 3. Mean CA results for each run along with chance levels results

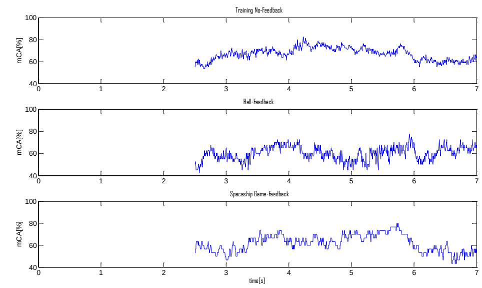

Figure 2. Time course of mean classification accuracy (mCA) for each run: no FB (top), ball FB (middle) and spaceship FB (bottom)

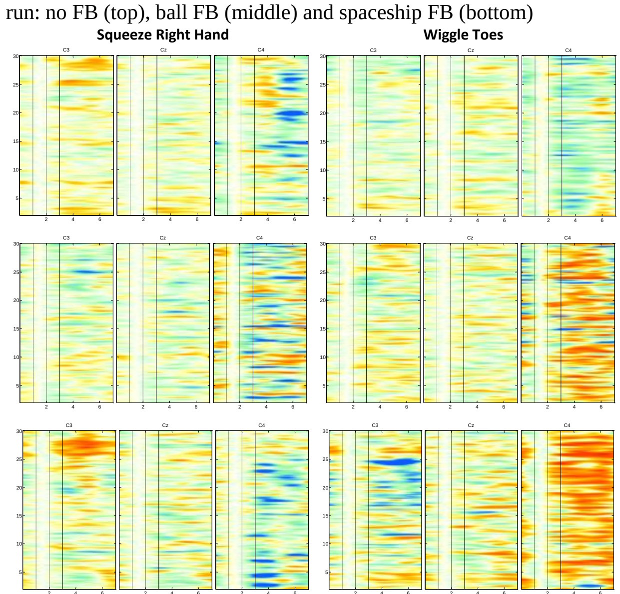

Figure 3. ERDS maps for the runs, channels C3, Cz and C4 for squeeze right hand (left column); wiggle Toes (right column); No feedback (top); Ball feedback (middle) and Spaceship game feedback (bottom). Blue=ERS; Red=ERD;

and a non-parametric Wilcoxon signed rank tests are used to confirm that significant activations were achieved. Theoretically, baseline performance should be 50% for a 2-class problem. We also compare the results with actual chance levels for a comparable number of trials in a 2-class BCI task based on the simulation study presented in [15]. An ERDS analysis is also presented.

3. Results

The results are presented in Table 2. The mCA in the time after each tone was significantly greater ($p<0.01$) than that achieved in the baseline period in the first two runs. The difference between baseline and event is not significant for run 3 involving the spaceship feedback. In the case of the spaceship game the feedback (moving spaceship) is on the screen continuously so the participant can try to modulate its position even when there is no target specified (when no asteroids are to be avoided) hence the difference between baseline and peak is likely to be less significant. Also, there are less trials in run 3 (43 trials). Figure 2 shows the time course of mCA for each of the runs. A clear increase from circa 50% in the baseline (<3s) towards a peak circa 3s later is evident for the feedback runs. Figure 3 shows the ERDS plots where the reference interval is taken between 1-2s. Noise effected channel C4 during the feedback runs however there is a clearly distinguishable difference on this channel for both MI, with predominantly ERS during squeeze hand and ERD during wiggle toes MI. There is an observable upper beta ERD on channel C3 during squeeze hand which is not observable during wiggle toes in run1 (no feedback). This upper beta ERD is less observable on C3 during the ball feedback but the difference between both imageries is clearly pronounced during the spaceship game feedback where a beta ERS is observable on the C3 channel for wiggle toes.

4. Discussion and Conclusion

Although this participant's diagnosis is minimally conscious the results provide substantial evidence that he is aware but is in a completely locked-in state. The results may not be directly comparable to the results of [2] as more verbal cues were given during the session along with significant amount of feedback however the results do suggest the participant is capable of sustained attention, response selection and language comprehension. Follow up assessment will limit the verbal cues to determine the participants working memory capacity. The results are very positive for the participant and his family, given the fact that he has not communicated for over 11 years and his level of awareness was thought to be that of minimally conscious. At the onset of the trial the participant seemed uninterested and inattentive. When the feedback was presented to the participant, particularly when the spaceship game was introduced there was a noticeable difference in the participant's demeanor, which was acknowledged by his family. During feedback a family member actually provided verbal encouragement to "dodge the asteroids". There is clear evidence here that real-time feedback influenced the outcome of the experiment. Had the detection of awareness only followed a no-feedback protocol with no maintaining wakefulness during the 'boring' part of the session (some BCI users find training with no feedback unintuitive) the participant may not have been engaged as much and the results therefore less conclusive. It is therefore recommended to apply real-time feedback in the detection of awareness. The results presented here indicate that the participant is actually better than some able-bodied naive BCI users. A follow up study is planned to conduct a one week intensive motor imagery based BCI session to determine if this participant would benefit from a motor imagery BCI on a day-to-day basis. This will follow a similar protocol to that recommended here [16] and described in [17].

Overall, the results demonstrate, for the first time, the feasibility of using a 3 channel motor imagery based BCI for the detection of awareness in the minimally conscious and enabling real-time control of an on-screen object by a person who has been completely locked-in for over 11 years, after less than 2 hours training.

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